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Multi-Media Microbiological Risk Assessment Methodology for Municipal Wastewater Sludges

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ABSTRACT

In order to reduce the risk of municipal sludge to acceptable levels, the U.S. Environmental Protection Agency has undertaken a regulatory program based on risk assessment and risk management. The key to such a program is the development of a methodology which allows the regulatory agency to quantify the relative risks arising from a given reuse/disposal option. This paper briefly describes the development of risk assessment methodology for future development of pathogen criteria for land application and distribution and marketing of municipal sludge.

INTRODUCTION

On September 13, 1979, Code of Federal Regulations Part 257, "Criteria for Classification of Solid Waste Disposal Facilities and Practices", was published. This regulation established criteria or standards against which solid waste disposal facilities and practices are to be compared. Failure to meet these criteria would indicate a reasonable probability of adverse effects on health or the environment. Consequently such non-conforming practices are prohibited under the Resource Conservation and Recovery Act (RCRA) and those practices related to sludge utilization and disposal are also prohibited under Section 405 of the Clean Water Act.

The regulation was written with an awareness that a substantial fraction of the sludge produced at municipal publicly owned treatment works (POTWs) was being used in agriculture, generally in a carefully controlled manner, but in other cases in a fashion that could endanger public health. Consequently, regulations were necessary, but they had to be carefully crafted so that they prevented bad practice yet allowed constructive use of a valuable resource.

The regulation specifically addressed potential impacts of pathogens, cadmium and polychlorinated biphenyls. With regard to pathogens, the basic principles that were used in framing the regulation are the following: (1) conventional treatment processes such as anaerobic digestion, which are used to eliminate the noxious odor of sludge, reduce but do not eliminate all pathogens from sludge, (2) processes such as pasteurization essentially eliminate all pathogens from sludge, although disposal costs are increased, (3) conditions on the soil are adverse to human pathogens adapted to warm-blooded animals so survival of most pathogens (except for helminth eggs) after disposal to the land is generally short, and (4) control of access to the site where sludge is used reduces risk of exposure of the public to sludge pathogens, particularly for helminth eggs which are less likely to move from the site than other pathogens.

The structure of the regulation for sewage sludge is given in Figure 1. As the figure shows, sludge can be disposed or used on the land if it is treated by a "process to further reduce pathogens" (PFRP). If pathogen reduction is less than that produced by a "process to significantly reduce pathogens" (PSRP) (equivalent to well-conducted anaerobic digestion), sludge cannot be utilized on land. If the sludge is treated by a PFRP (the equivalent of pasteurization), there are not restrictions relating to pathogen content. If a PSRP is utilized, sludge may be used if the indicated restrictions as to the grazing, nature of crop, and access are followed.

One of the major potential hazards from sludge use comes when the public can contact it in gardening or when it is carried by crops into the home. The PFRP process is needed if access is not restricted and crop types and grazing are not controlled. If only a PSRP process is used, access restrictions are needed if food chain crops that touch the sludge are grown. The time-of-access restriction is related to the expected survivability of the hardiest pathogen - the helminth eggs. If there is no treatment of the sludge, potential risk is considered too great to allow any utilization on land.

The use of septage on the land also falls

under the regulation (Figure 2), although the regulation treats septage and sludge in slightly different ways. Untreated septage may be applied to land for grazing or for crops not grown for direct human consumption. Sludge requires both access control and a PSRP for any application to the soil. The generally rural nature of septage disposal, the small scale of the disposal operation, and the long-term storage in the septic tank were factors in allowing less stringent requirements for septage than for sludge.

PATHOGENS OF CONCERN

A significant proportion of the bacteria, viruses, protozoa, and eggs of parasitic worms in wastewater become concentrated in sludge during wastewater treatment. A portion of these organisms may be pathogenic (disease-causing). Although pathogen abundance is difficult to measure directly, pathogen reduction can be estimated from the reduction in concentration of indicator organism. Sludge treatment processes can substantially reduce pathogen levels. However, concentrations of certain organisms are not significantly reduced in some treatment processes.

Land application of sludge consists of the low-rate application compared with a purely waste disposal operation, to agricultural, forest, or reclaimed land of municipal wastewater sludge which has been "stabilized" in some way, e.g. anaerobic digestion or composting. Land application of sludge is an important and probably growing practice in the U.S. This is indicated by the results of a recent survey of 1008 POTWs, accounting for over 2 million dry metric tons per day of sludge [1]. The survey found 17% of the total sludge to be utilized in large scale food-chain land-spreading, 12% in large scale nonfood-chain landspreading, and 21% in distribution and marketing systems (much of which probably ends up in garden and lawns).

Most microbial species contained in raw sewage are concentrated in sludge during primary sedimentation. Enteric viruses have too little mass to settle alone but, because of their strong binding affinity to particulates, they are also concentrated in sludge [2].

Table 1 presents typical, average densities that have been found by a number of investigators [2]. Different sludges may contain significantly more or less of any organism as determined primarily by the sewage from which the sludge was derived. The quantities of pathogenic species will be especially variable depending on which are circulating in a community at any particular time. Indicator organisms are normally present in fairly constant amounts. Because the concentrations determined in any study are dependent on particular assay procedures to detect each microbial species, these concentrations are only as precise as the assays themselves. This point is especially relevant in regard to viruses in environmental samples of which only a small percentage are normally detected by even the best procedures.

Pathogens in secondary treatment of sludges may also be of concern following biological treatment of wastewater. Microbial populations in sludges following these treatments will depend on the initial concentrations in the wastewater, the die-off or growth during treatments, and the association of these organisms with sludge. Some treatments, such as the activated sludge process, have a deleterious effect on enteric microbial species. For example, viral and bacterial pathogens have been shown to be reduced in concentration by activated-sludge treatment. Even so, the ranges of concentrations in secondary sludges obtained following this and most other secondary treatments are usually not significantly different from those of primary sludges. Examples are shown in Table 2 [2].

MULTI-MEDIA RISKS

Due to the potential public health impacts of pathogens found in sludge, it is imperative that risk assessment methodologies be developed for each sludge reuse/disposal option (land application, landfilling, and ocean disposal) to ensure protection of human health and the environment. The risk assessments should address bacterial, viruses, protozoa, helminths and fungi. The fate and transport of the pathogens in each medium (e.g., groundwater) should be investigated and assessed as to the risks to human health and the environment.

In order to reduce the risk of municipal sludge to acceptable levels, the U.S. Environmental Protection Agency has undertaken a regulatory program based on risk assessment and risk management. The key to such a program is the development of a methodology which allows the regulatory agency to quantify the relative risks arising from use of a given option. This paper will present the development of risk assessment methodology for future development of pathogen criteria for land application and distribution and marketing (D&M) of municipal sludges. The methodology utilizes a computer model that was originally developed in 1980 by the U.S. Environmental Protection Agency and the

U.S. Department of Energy [3].

The criteria used to select representative pathogens for consideration in the model are: the pathogen is known to be present in municipal sludge; the pathogen is known to cause human disease; more data are available for one pathogen than for others in the same microbial group; and the pathogen has survivability similar to other members of the group; minimal infective doses (MIDs) are known; the pathogen selected survives outside the human host; the infective routes (that is, ingestion, inhalation, or skin contact) are known.

The pathogenic organisms that were selected as representative of pathogen presence in municipal sludges are:

1. Salmonella spp. as examples of pathogenic enteric bacteria.
2. Enteroviruses as examples of enteric viruses.
3. Entamoeba histolytica and Giardia lamblia as examples of the parasitic protozoans.
4. Ascaris lumbricoides and A. lumbricoides var. suum as examples of the helminths.
5. Aspergillus fumigatus as example of fungi.

FATE AND TRANSPORT

A total of eight sludge utilization pathways are included in the present model and are numbered I-VIII. Three of the pathways involve use of dewatered sludge for commerical applications:

I. Fertilizer for Crops Destined for Human Consumption,
II. Fertilizer for Pasture Crops, Golf Courses, Recreational Fields and Related Uses, and
III. Fertilizer for Horticultural Purposes and for Crops that are Processed Before Animal Consumption.

Two of the pathways involve use of dewatered sludge for residential purposes:

IV. Fertilizer for Vegetable and Flower Gardens, Shrubbery and Related Uses in the Residential Environment, and
V. Fertilizer for Residential Lawn Soil and Related Uses.

Three of the pathways involve use of liquid sludge also for commerical applications:

VI. Fertilizer for Crops Destined for Human Consumption,
VII. Fertilizer for Pasture Crops, and
VIII. Fertilizer for Crops that are Processed Before Animal Consumption.

HUMAN EXPOSURE ROUTES

The exposure to sludge pathogens was determined in five types of human exposures, including onsite person (e.g., workers, gardeners, and observers), food consumers (e.g., humans, animals), groundwater drinker (e.g., humans, animals), offsite pond swimmer and offsite pond drinker (e.g., humans, animals). Each exposure level was accumulated over a 24 hour period. The amount of exposure was determined by the number of sludge pathogens consumed or inhaled during that time period. This number, in turn, was determined by the concentration of pathogens in the consumed materials (determined in each exposure pathway) multiplied by the volume of mass of material consumed.

The eight pathways were each composed of compartments and pathogen transfers between compartments. The compartments, as seen for example in Figure 3, are the various locations where sludge or sludge-associated pathogens exist in particular pathways. Figure 3 shows Pathway IV, where dewatered sludge is utilized as fertilizer for vegetable and flower gardens, shrubbery and related uses in the residential environment. The arrows indicate the transfer of pathogens to and between compartments. Other pathways are similar.

In each compartment, pathogens either increase or decrease or remain at similar levels with time, depending upon the microbial growth, dieoff, or no population changes. Movement between compartments will affect the populations in each compartment. Within each compartment, first-order, linear, differential equations are derived to compute the rate and direction of change in the pathogen populations and the effect that any subprocesses in a compartment may have on that population. The population changes in a compartment are assessed on the basis of time, temperature, moisture content, and the presence of nutrients, and other physical and chemical factors. The transfer of pathogens between compartments is described by a set of ordinary differential equations which were derived using conservative principles, environmental parameters and relationships, and which were developed from data obtained in the literature. These equations are then integrated to determine the pathogen populations in each compartment. Reference 3 describes the equations, transport parameters, and kinetic assumptions used in the model.[3]

MINIMUM INFECTIVE DOSE (MID)

The public health significance of pathogens in sludge depends not only upon human exposure levels but upon the events following exposure. One of the main factors that affects these latter events is the dose of any particular pathogen required to cause infection and illness.

Studies have been conducted to determine the infectious doses of all classes of enteric pathogens including viruses, bacteria and parasites. The results of these studies have been presented in various ways. For example, viral infectivity has been based on the dose required to infect 50% (HID_{50}), 10% (HID_{10}) or 1% (HID_{01}) of an exposed population [4]. In order to be conservative, the infectious dose used in this present study is the minimum (i.e. MID) that has been reported in the literature to cause any incidence of infection.

The infectious dose of any enteric pathogen must be quantified by an acceptable assay procedure. Infectious dose studies have relied heavily on *in vitro* viability assays to measure dose such as plaque formation (viruses) and colony formation (bacteria). Sometimes, however, dose has been based solely on particle counts such as cysts of *Giardia lamblia* [5,6]. In this latter case, the number of viable organisms consumed by subjects was not known. Even when viability assays are used, the efficiencies of these assays can dramatically alter the results. For example, merely changing the cell line used to quantify echovirus-12 by plaque formation in a minimal infective dose study increased the sensitivity of the assay 33-fold, which increased the calculated HID_{50} necessary to infect 50% of the subjects, from 30 plaque-forming units (pfu) to >900.

CONCLUSION

In conclusion, the computer model developed was designed to aid in sludge management decisions by comparing the relative risks of alternatives as sludge is applied to cropland and grazed pasture as a fertilizer, and used as a soil conditioner. After extensive further development and evaluation, this computer model will be useful for exploring relative health risks associated with a variety of user-defined sludge treatment and application scenarios, and could eventually provide a basis for reevaluation of the existing PSRP/PFRP regulatory approach.

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Table 1
Densities of Microbial Pathogens and Indicators in Primary Sludges

Type	Organism	Density (number/g dry weight)
Virus	Various enteric viruses	10^2-10^4
Bacteria	Bacteriophages	10^3
	Total coliforms	10^8-10^9
	Fecal coliforms	10^7-10^8
	Fecal streptococci	10^6-10^7
	Salmonella sp.	10^2-10^3
	Clostridia sp.	10^6
	Mycobacterium tuberculosis	10^6
Parasite	*Ascaris* sp.	10^2-10^3
	Trichuris vulpis	10^2
	Toxocara sp.	10^1-10^2

Reference 2

Table 2
Densities of Pathogenic and Indicator Microbial Species in Secondary Sludges

Type	Organism	Density (number/g dry weight)
Virus	Various enteric viruses	$3x10^2$
Bacteria	Total coliforms	$7x10^6$
	Fecal coliforms	$8x10^6$
	Fecal streptococci	$2x10^2$
	Salmonella sp.	$9x10^2$
Parasite	*Ascaris* sp.	$1x10^3$
	Trichuris vulpis	$1x10^4$
	Toxocara sp.	$3x10^2$

Reference 2

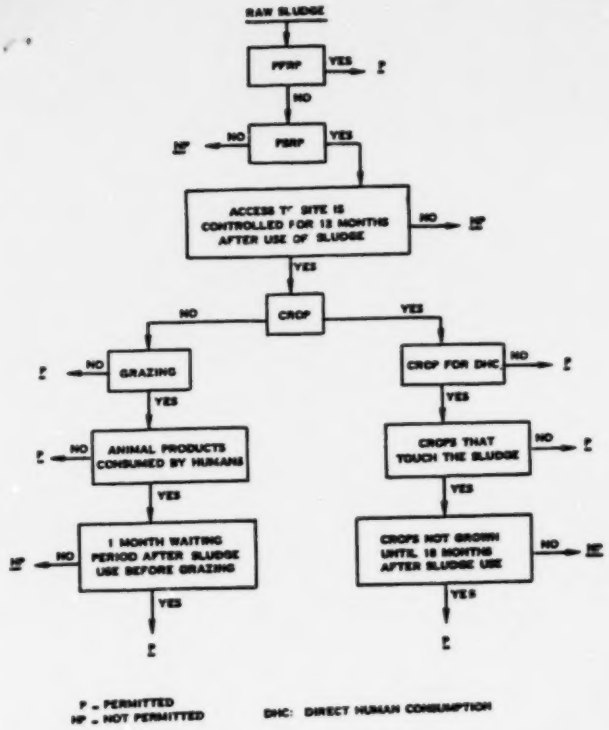

Figure 1
Use of Sludge on Land, RCRA Criteria

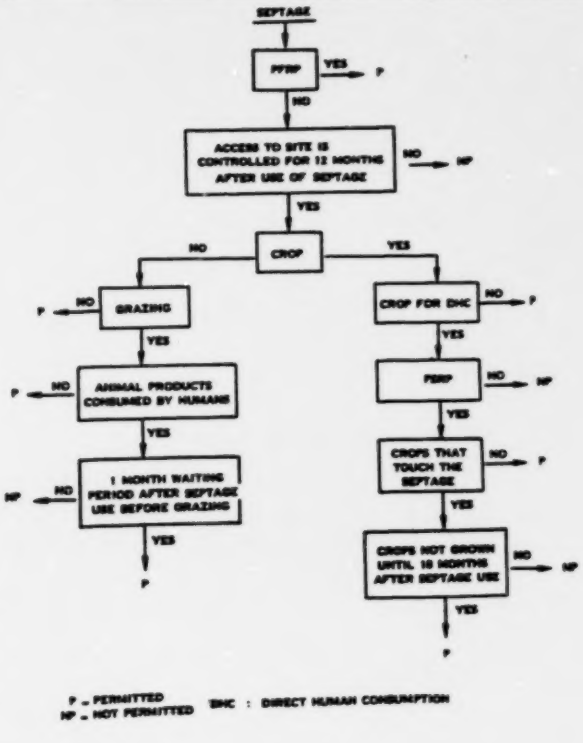

Figure 2
Use of Septage on Land, RCRA Criteria

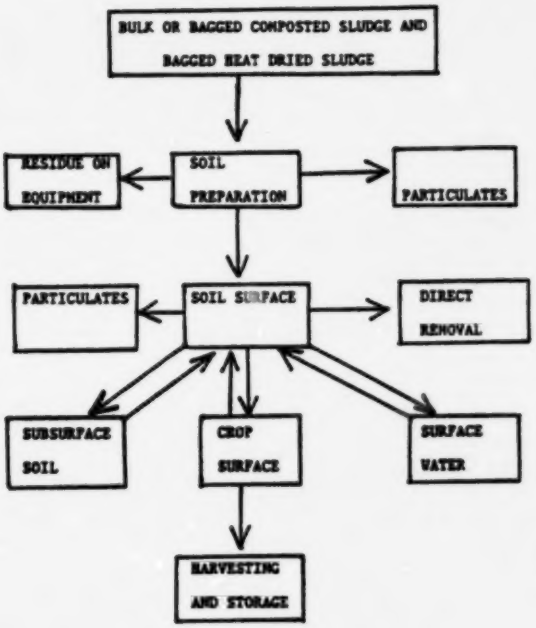

Figure 3
Pathway IV, Dewatered Sludge Utilization as Fertilizer for Vegetable and Flower Gardens, Shrubbery and Related Uses in the Residential Environment (arrows indicate transfer of pathogens to and between compartments).